



# Status of experiments using the KURRI 150 MeV ADSR FFAG

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With thanks to the KURRI-FFAG collaboration  
including members from Japan, UK & US

# Motivation: High Power FFAGs

FFAGs have not yet demonstrated:

1. High bunch charge capability
2. The fundamental limitations of FFAGs with high current beams
3. High repetition rates in the kHz range or CW beams
4. Better reliability than a synchrotron

In these experiments, we can potentially start to address (1) and (2).

# 150 MeV ADSR FFAG

Scaling FFAG

Injection 11 MeV, H- charge exchange  
up to 100 or 150 MeV

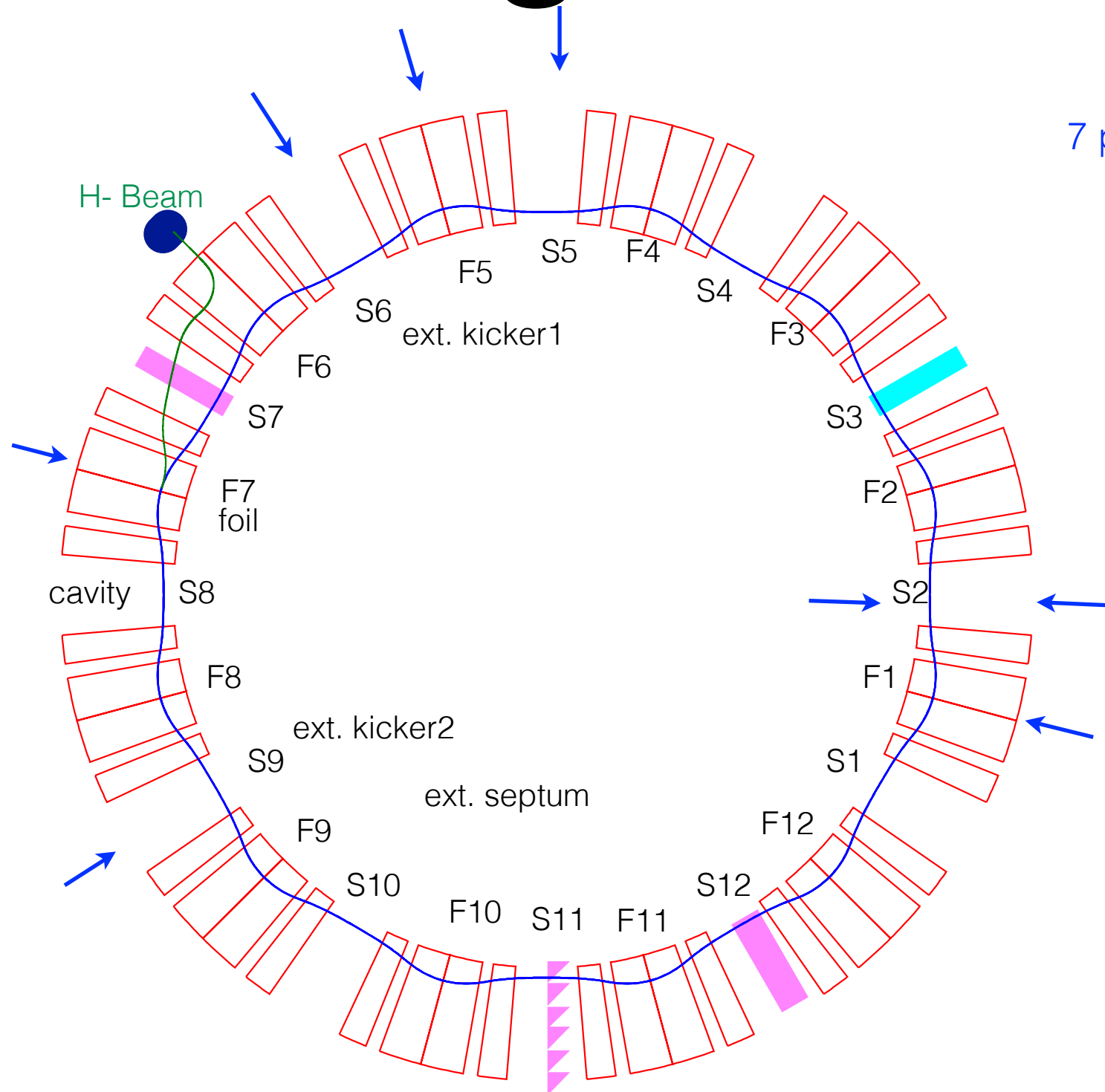


(for more details see Y. Ishi's talk, from Monday)

# Outline

- Orbit matching
- Closed orbit distortion & correction
- Field index
- Dispersion
- Energy loss on the foil

# Diagnostics in the ring



## List of monitors

7 ports for radial probes ( blue arrow, ICF70 )

4 portable radial probes remote cntrl'd

2 portable radial probes manual cntrl'd

1 unportable radial probe ( green arrow )

3 bunch monitors

1 faraday cup / 1 screen monitor

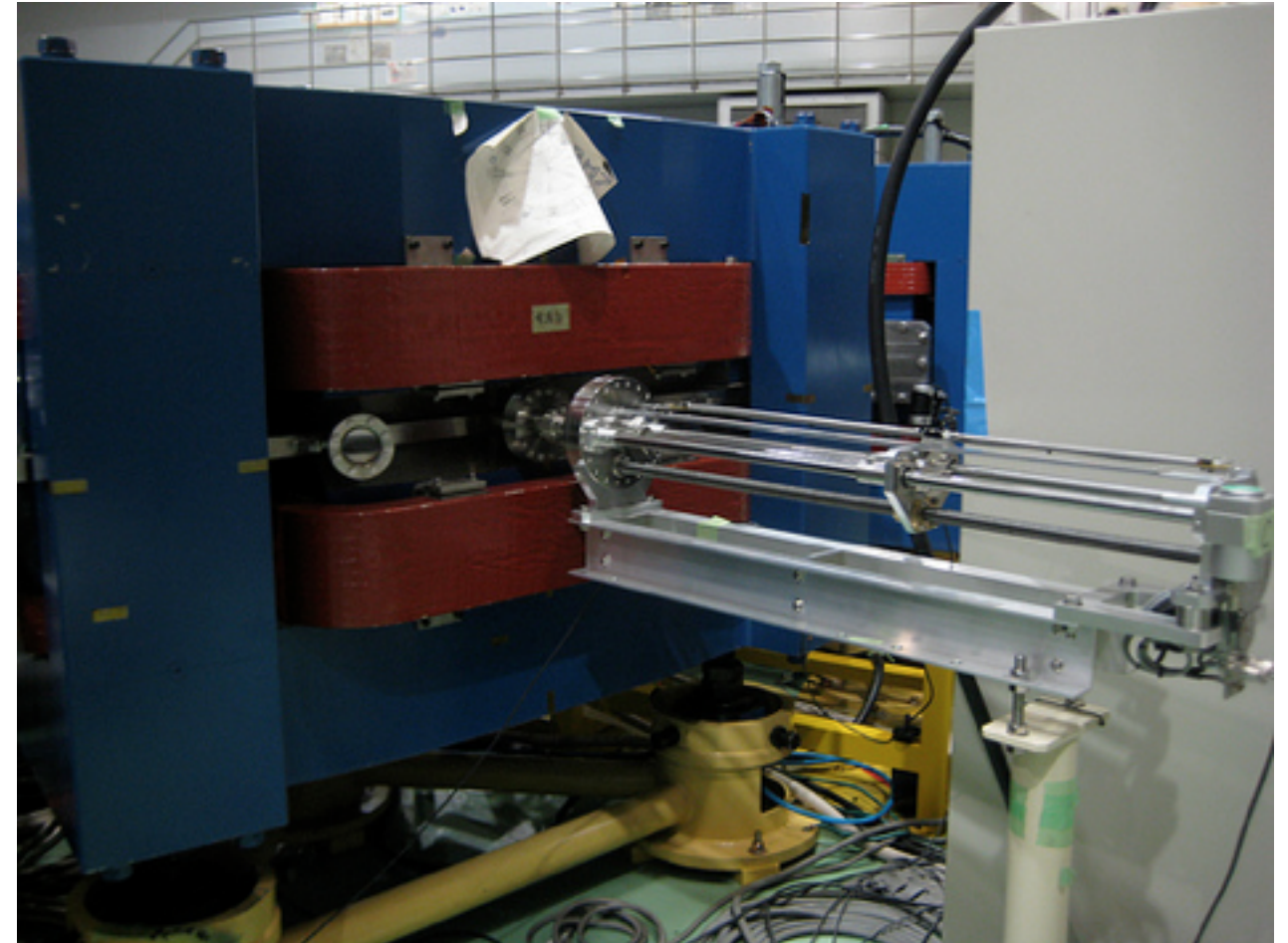
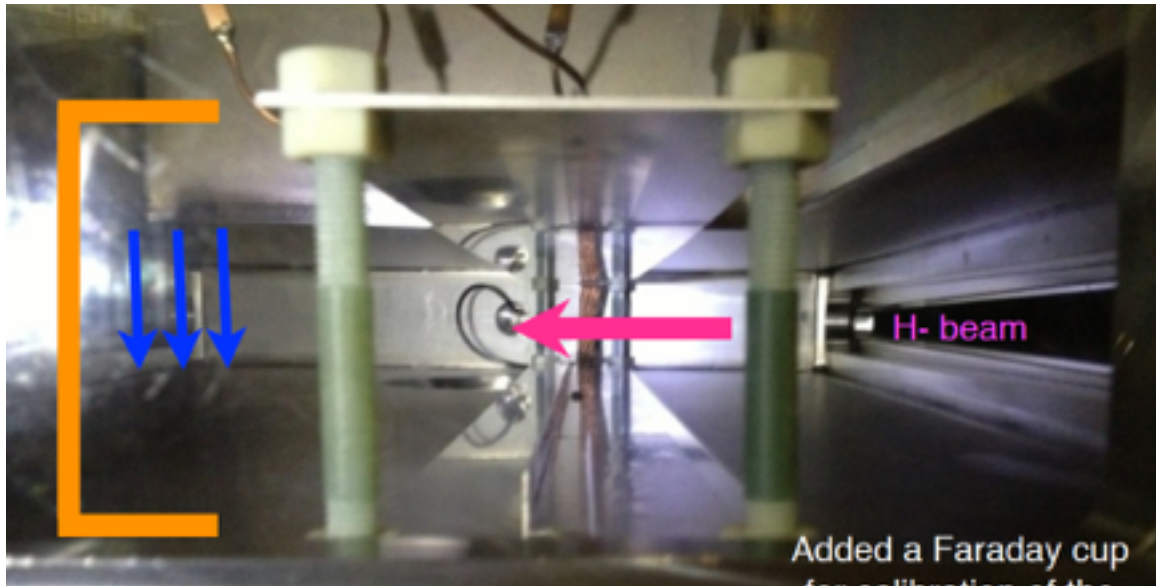
1 perturbator

S1	<del>radial probe removed</del>
F1	radial probe
S2	radial probe / hor. perturbator
S3	vert. perturbator
S5	movable bunch mon.
F5	radial probe
S6	radial probe
(F6)	Faraday cup / screen monitor
S7	bunch monitor
F7	radial probe
S9	radial probe
S11	bunch mon.( array of triangle plates)
S12	bunch monitor

Diagram courtesy Y. Ishi



# Diagnostics used



# Orbit Matching

- The beam follows a complicated trajectory from the injection line through to the stripping foil.
- The horizontal orbit is currently optimised 'by hand' to ensure the largest transmission...
- centre of foil is not necessarily optimal...!

## Vertical matching:

Match the vertical orbit using 3 steerers in injection line, using vertical double plate BPM to minimise vertical coherent oscillation

Performed on 20/3/14 and again for more data on 24/3/14.

Showed existing empirical optimisation was fairly successful.

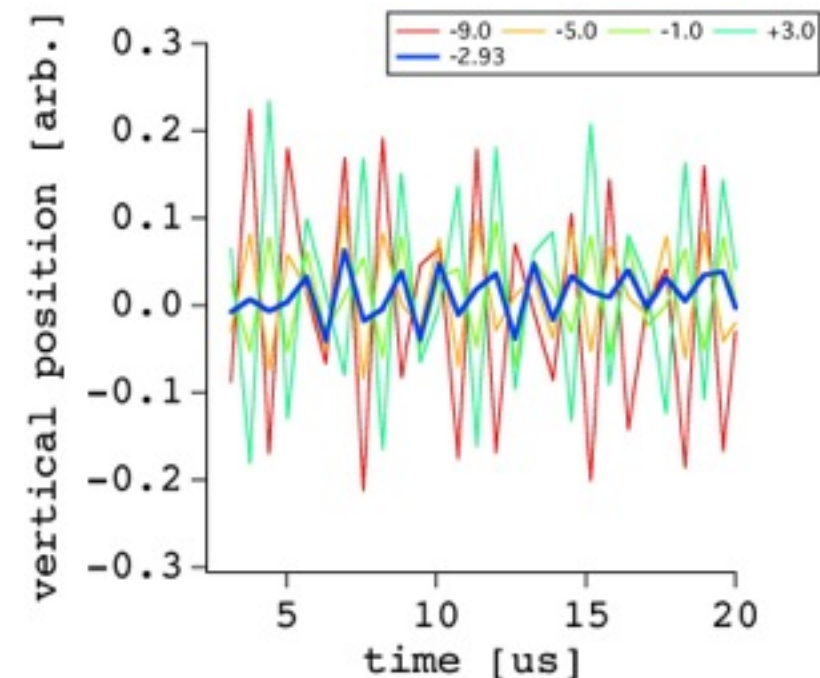
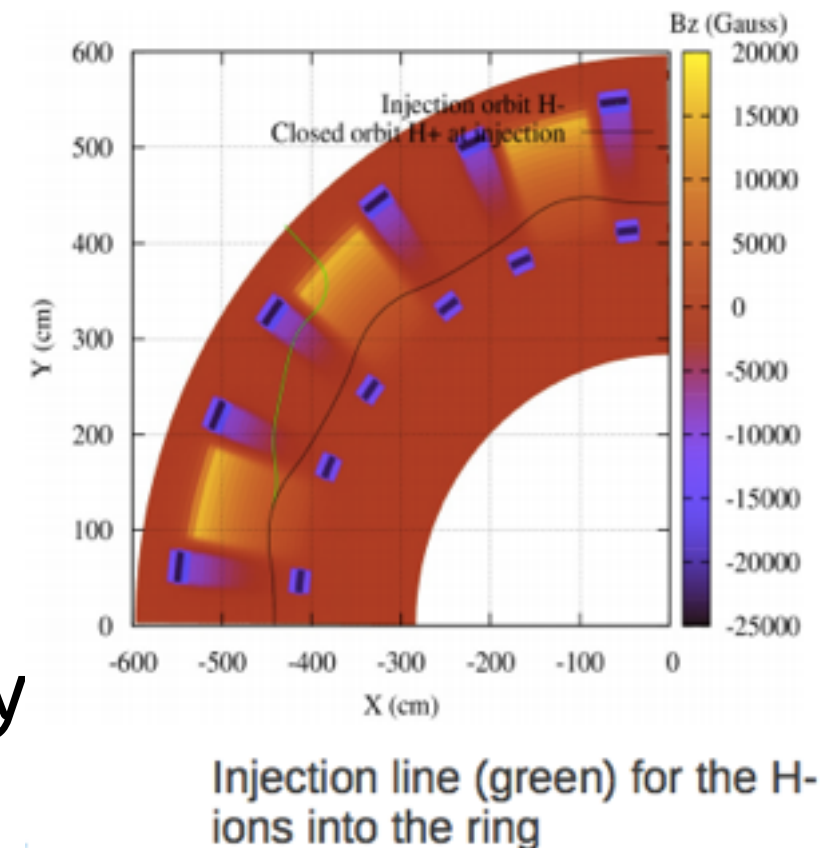
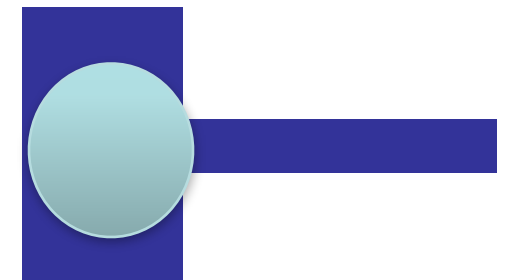
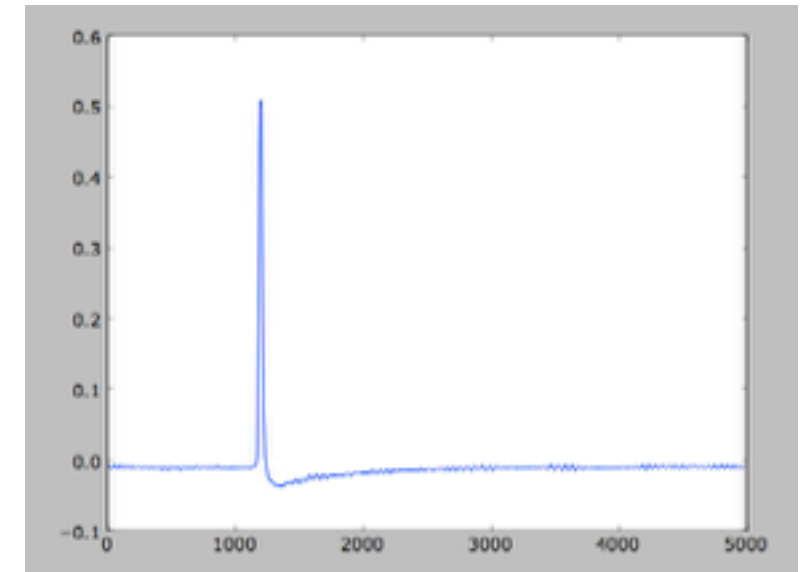
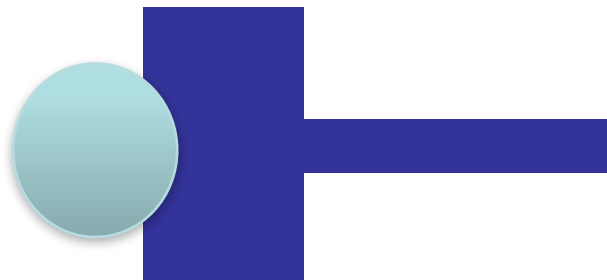
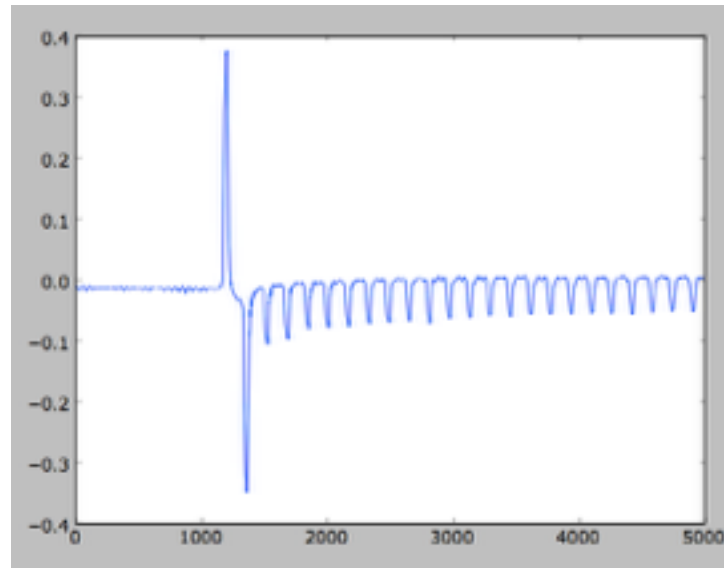
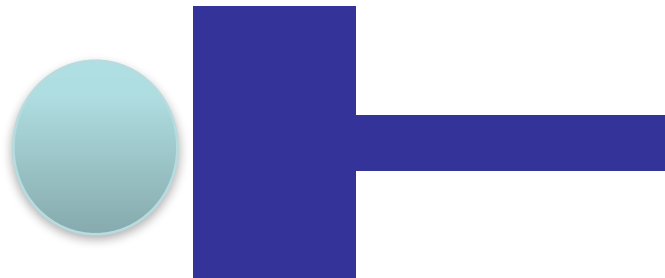
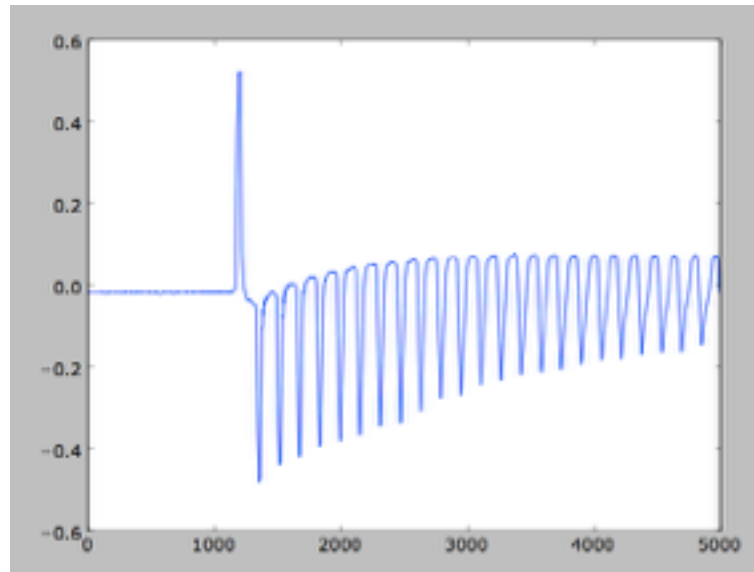


Figure from S. Machida, 24/3/14



# Closed Orbit Distortion (no RF)

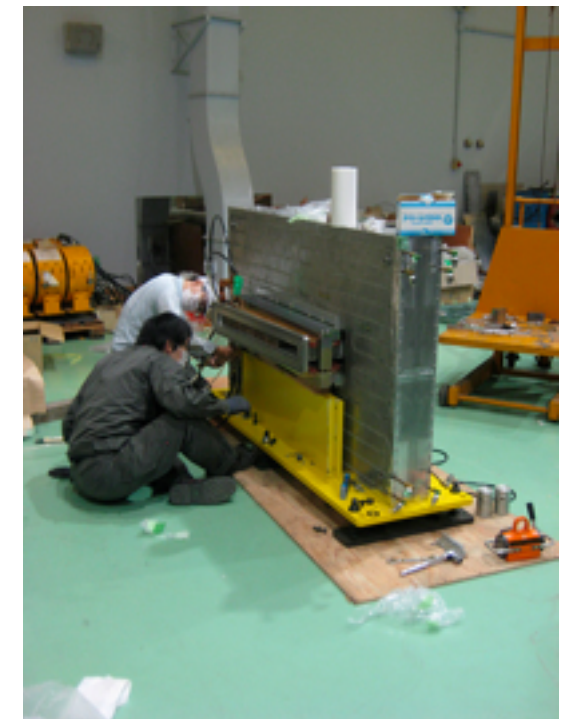
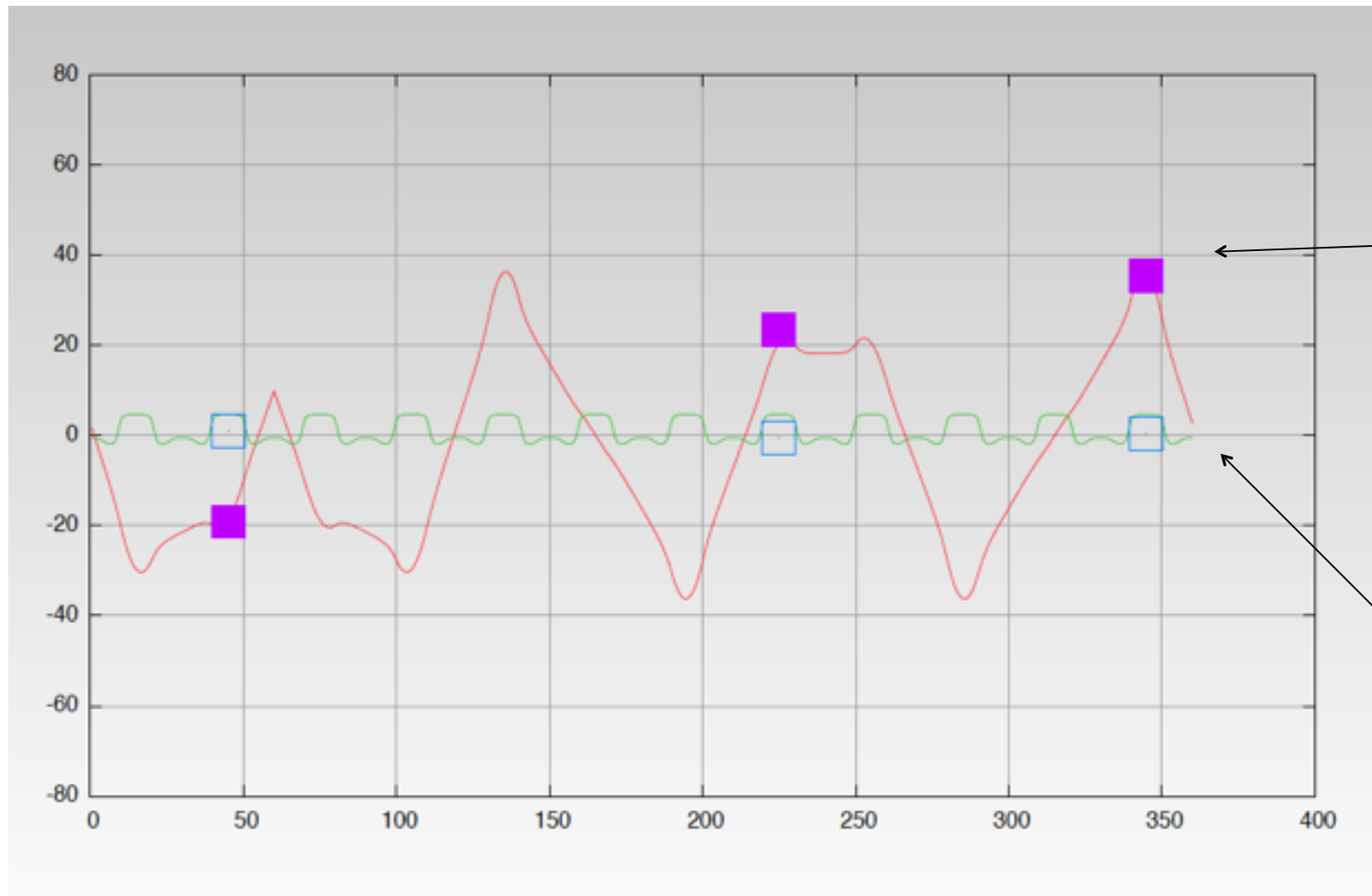


$$\text{Norm. response} = \frac{\text{peak height of } n\text{th turn}}{\text{peak height of } 0^{\text{th}} \text{ (H-)} \text{ turn}}$$



# Closed orbit distortion

Cavity 50 mrad kick



RF Cavity out during experimental run

COD with cavity

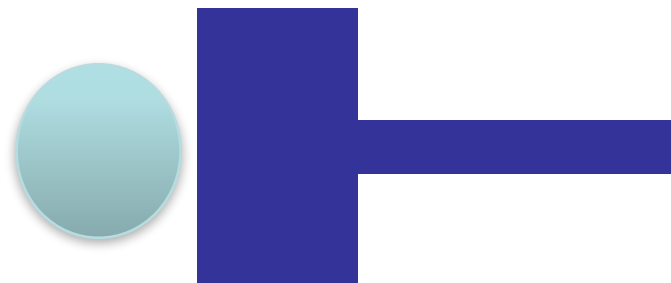
Without cavity

From Y. Ishi 1/11/2013

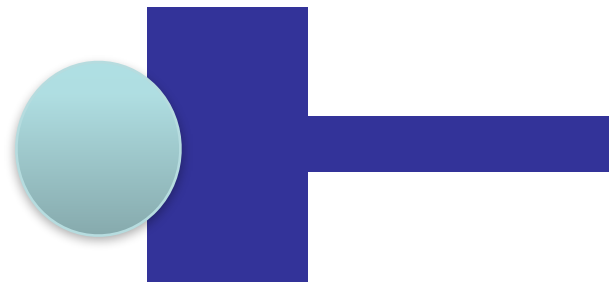
# Closed Orbit Distortion with RF

- Study effects of corrector with RF cavity in place
- Closed orbit measurement with acceleration

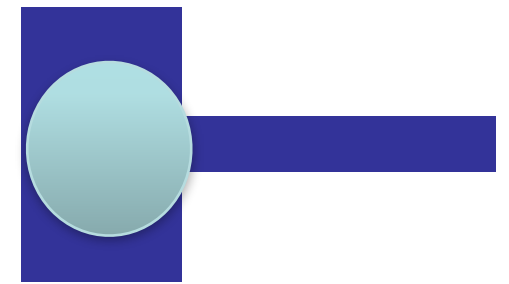
Beam spirals outward as it is accelerated



Probe doesn't stop beam



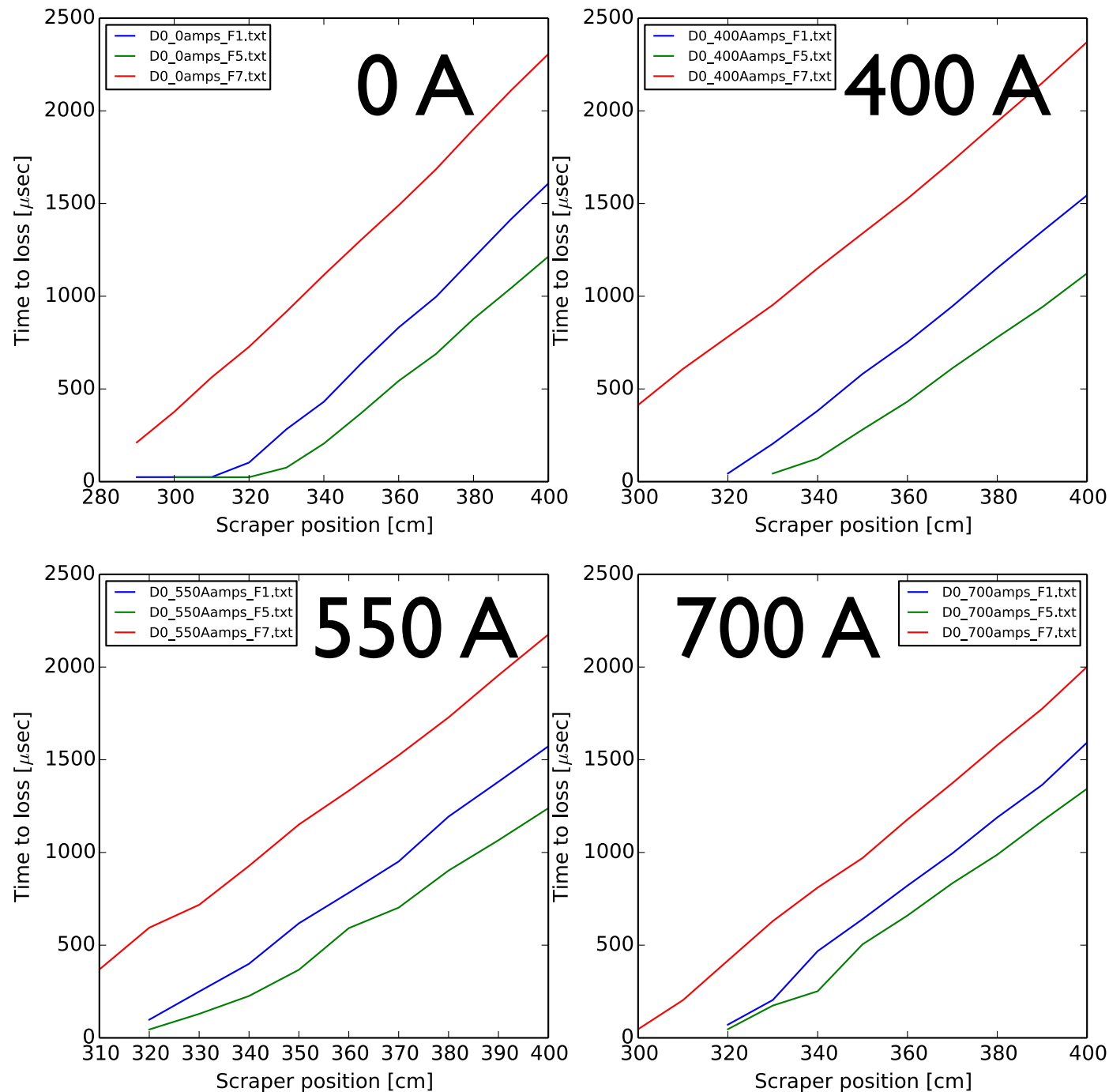
Probe stops part of beam



Probe fully stops beam



# COD Correction



Correction methods tried:

1) Main corrector pole

We achieve some correction,  
but it is not perfect, even with  
highest possible current

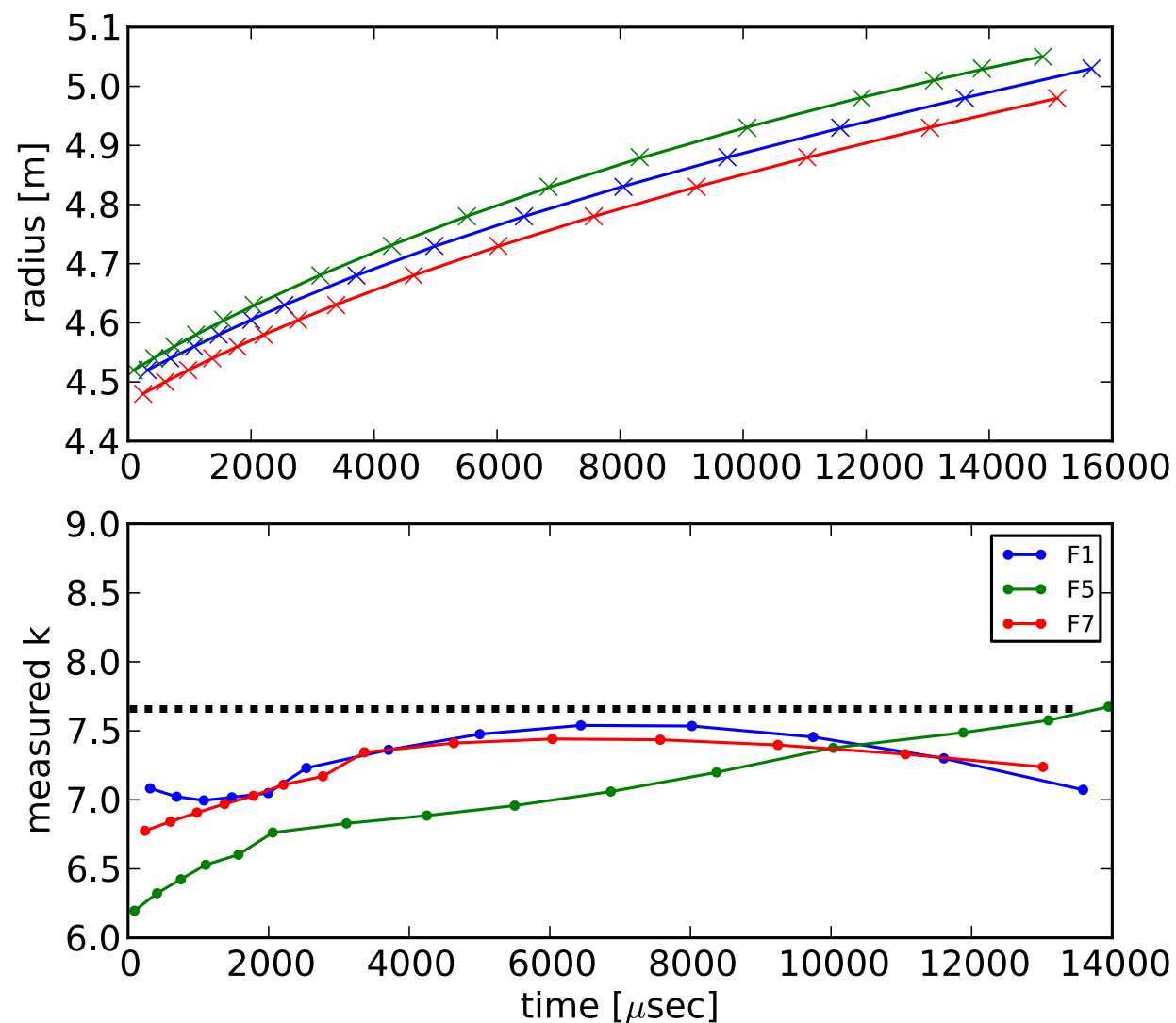
2) Additional coils on main  
magnet

Not successful at present -  
complex excitation of magnets

# Field index measurement

$$k = \gamma^2 \frac{df/f}{dr/r} - (1 - \gamma^2)$$

df/f from RF programme  
dr/r from measurement  
(also assume gamma from RF)





# Dispersion

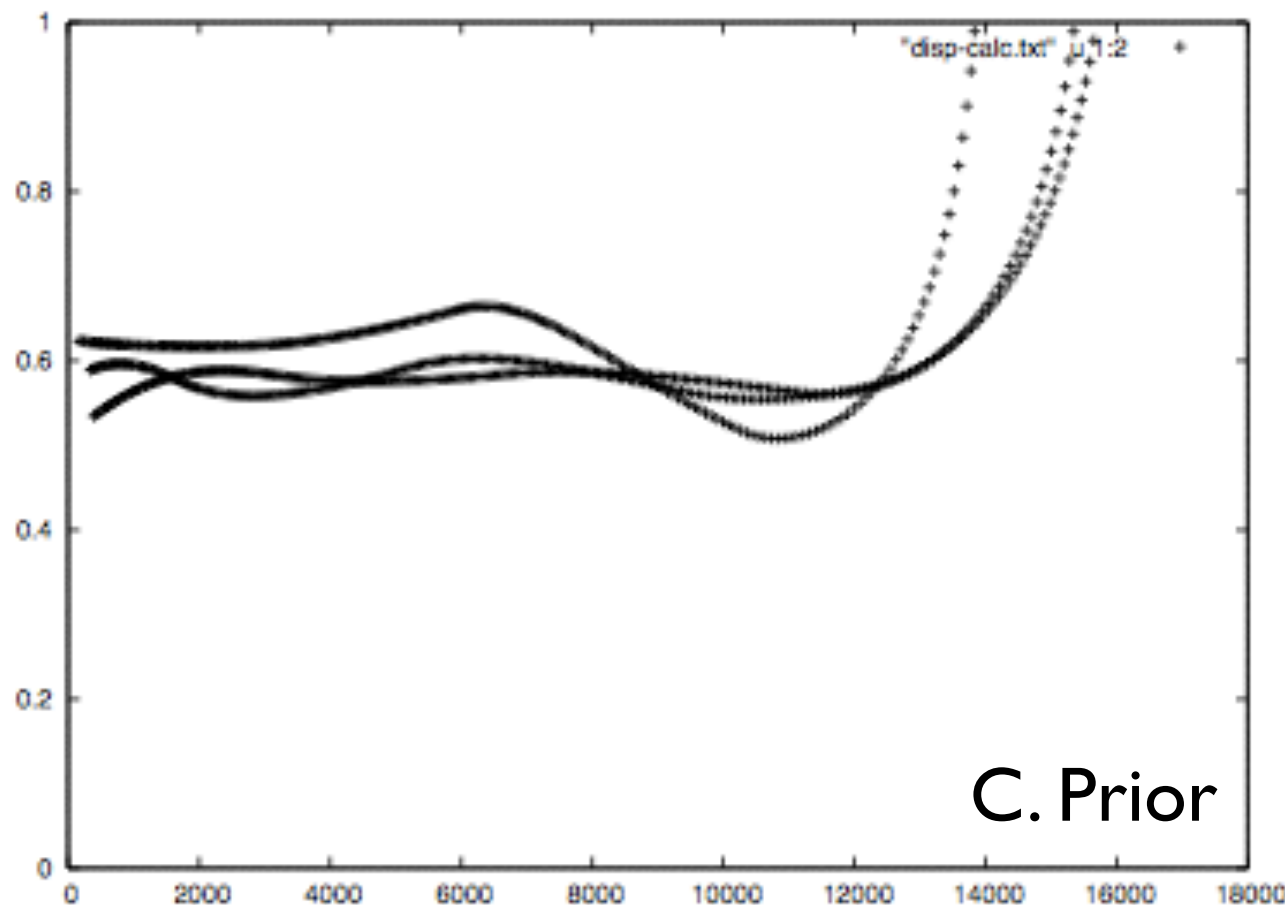
We have measured the dispersion:

- in the main ring
- at the position of the foil
- at a 'slit' before injection

All have different methods!

# Dispersion in the ring

- If we use the same data as field index measurement, we can calculate  $D = dr/(dp/p)$



$D \sim 0.6$

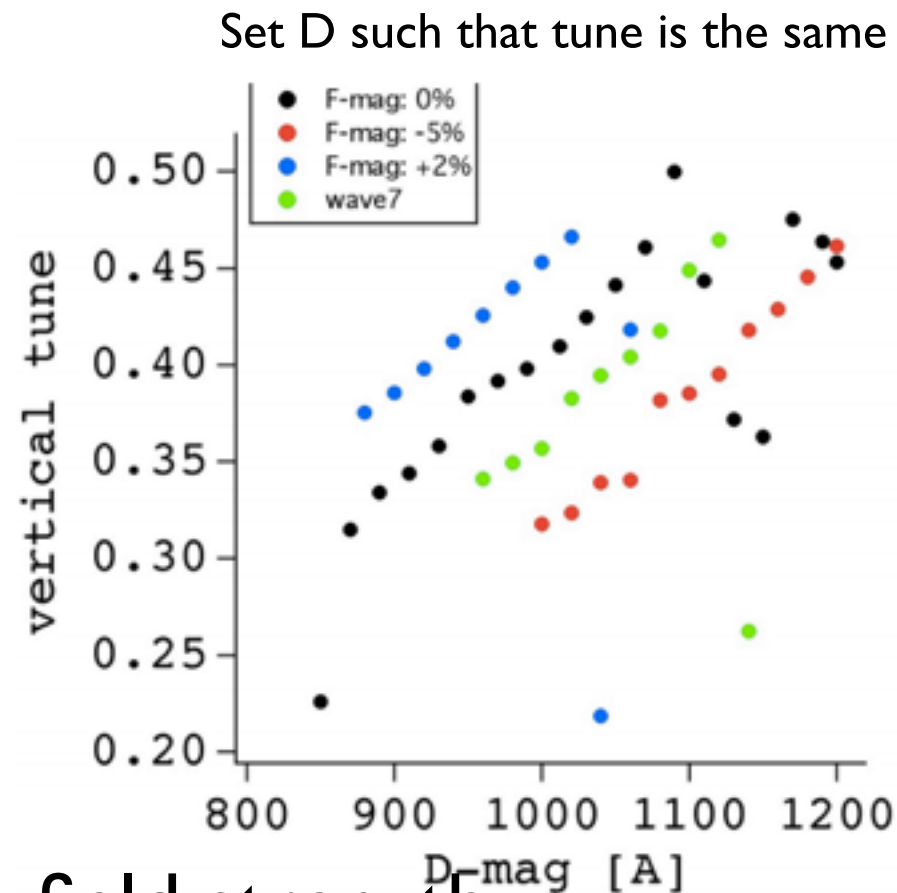
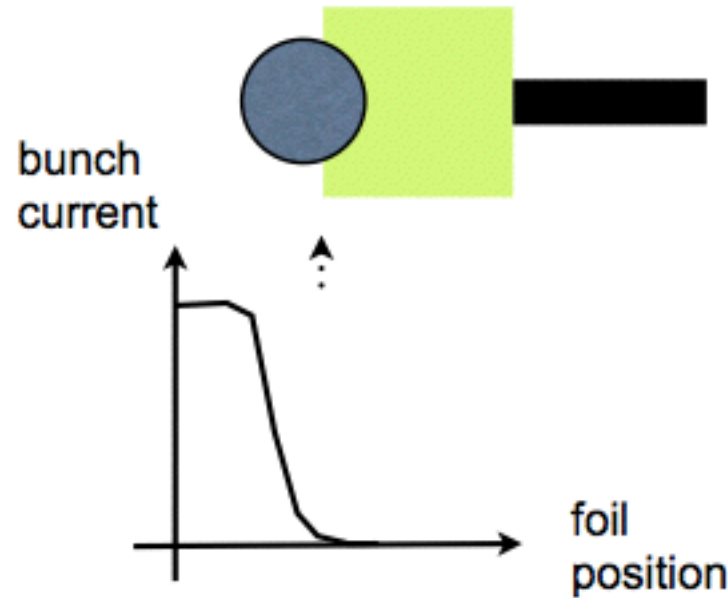
Three probes give  
slightly different results

we also did this for various corrector settings

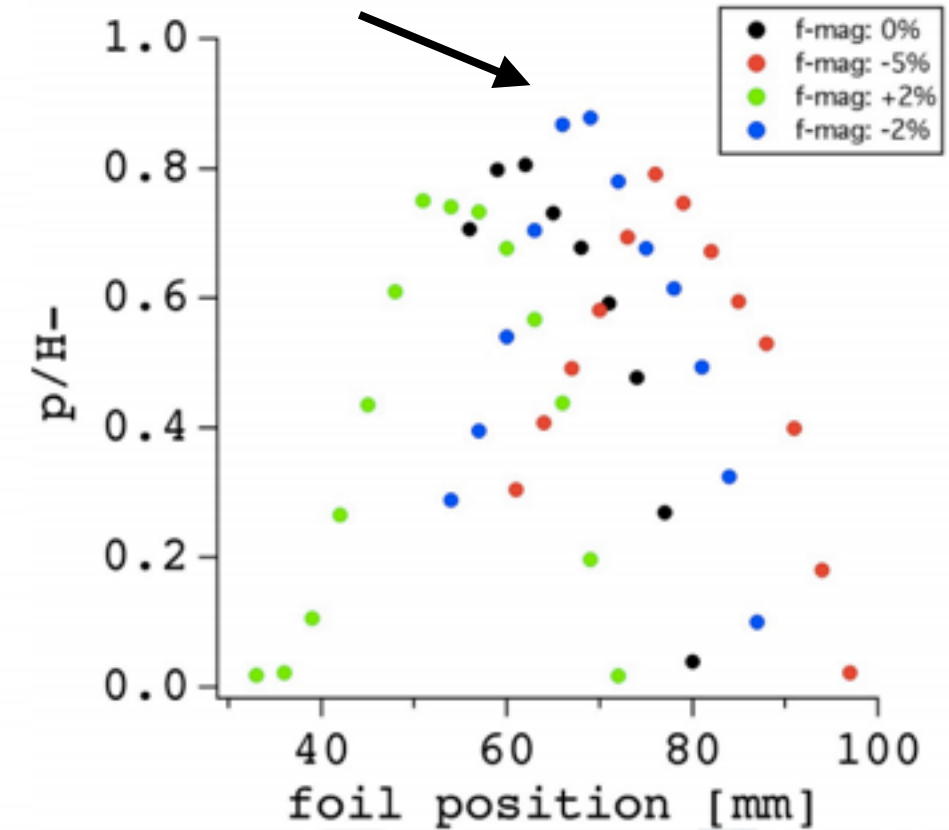
# Dispersion at the foil

## “Equivalent momentum method”

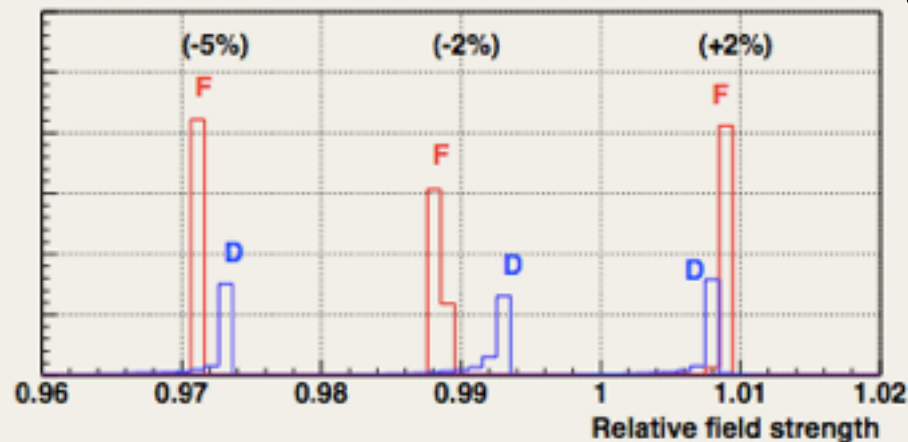
- Tune and profile at foil with different magnetic strength



no 'flat top'  
tells us beam bigger than foil!



Translate current to field strength



S. Machida

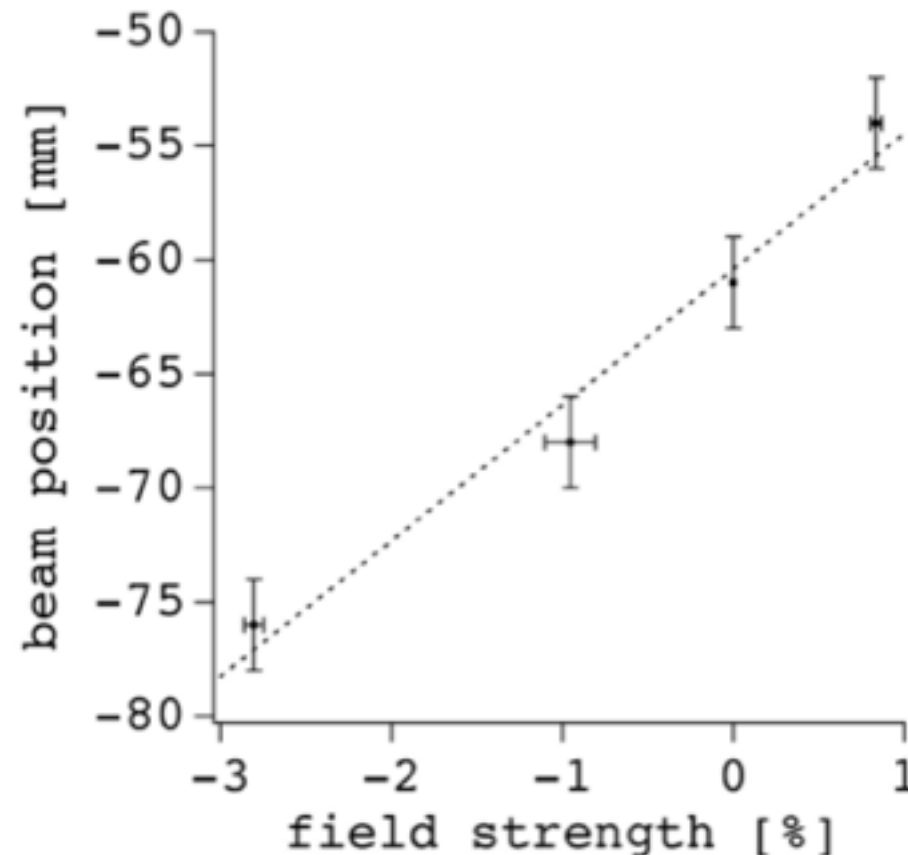
# Dispersion at the foil

- Measured dispersion function at foil after B calibration.

$$dr/(-dB/B) = -0.59 \pm 0.07$$

- Good agreement with Malek's calculation.

$$dr/(dp/p) = -0.57$$



nb. definition of dispersion in a transport line

$$\begin{pmatrix} D_f \\ D'_f \end{pmatrix} = \begin{pmatrix} m_{11} & m_{12} \\ m_{21} & m_{22} \end{pmatrix} \begin{pmatrix} D_i \\ D'_i \end{pmatrix} + \begin{pmatrix} D_p \\ D'_p \end{pmatrix} = \begin{pmatrix} 0.52 \\ -0.033 \end{pmatrix}$$

S.Y. Lee 'Accelerator Physics' pp.116  
'Dispersion vector'

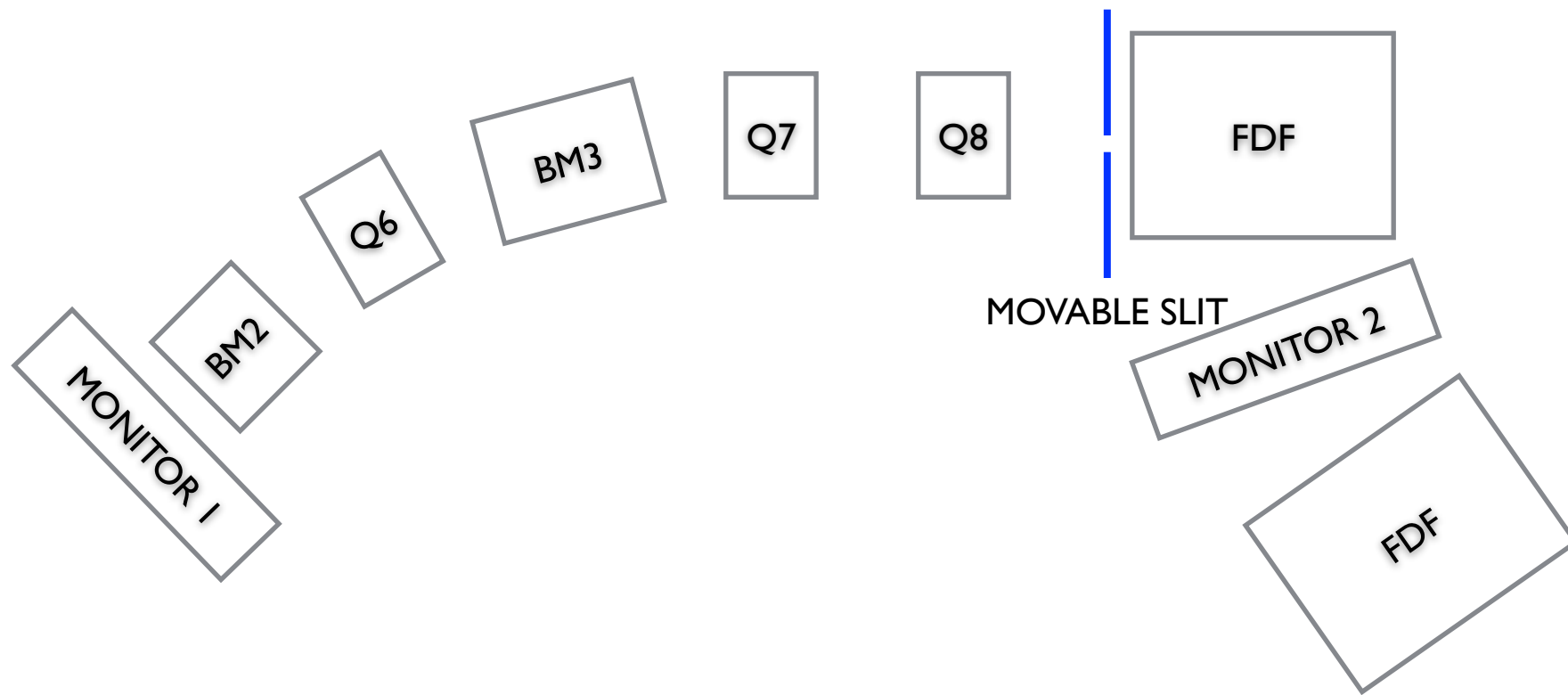
using transfer matrix from tracking

Is fairly consistent with 0.6 value in ring



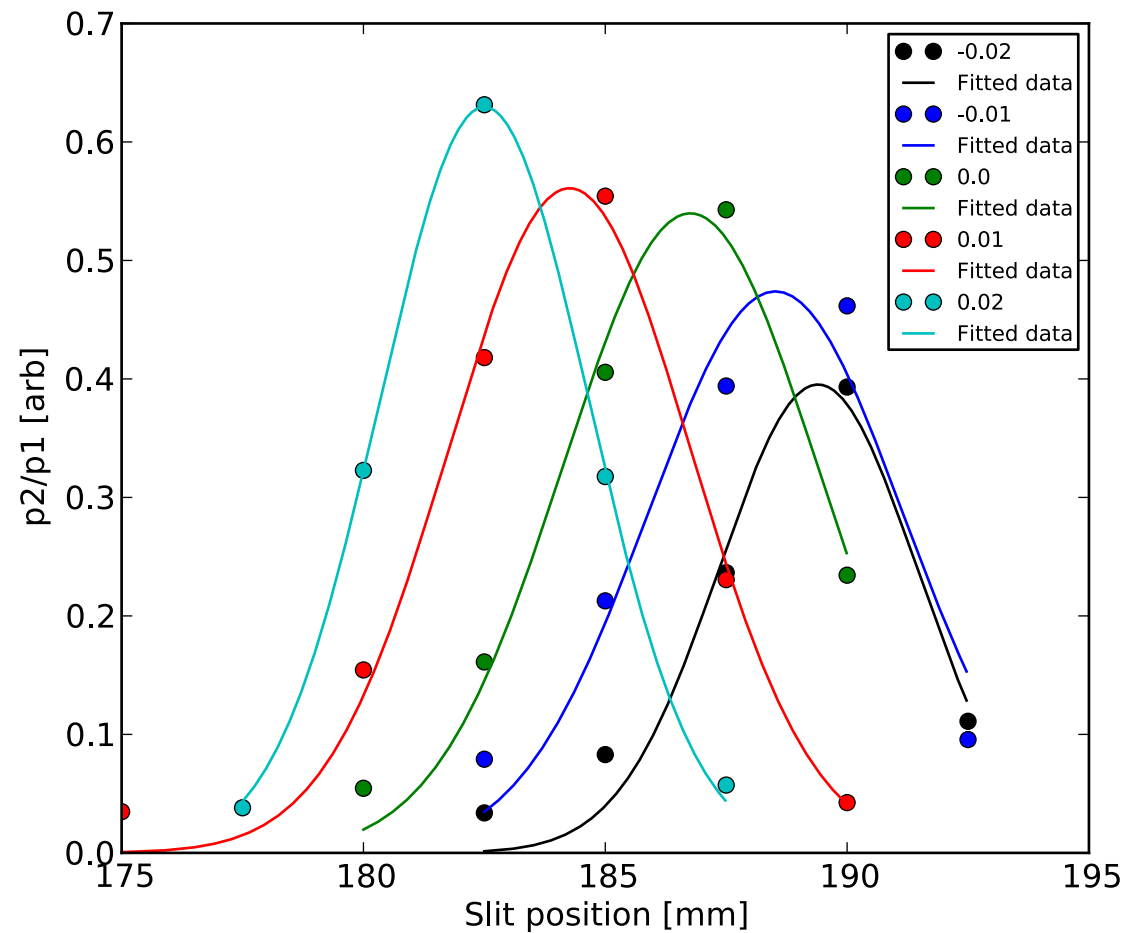
# Dispersion control:

## Dispersion at the slit before injection

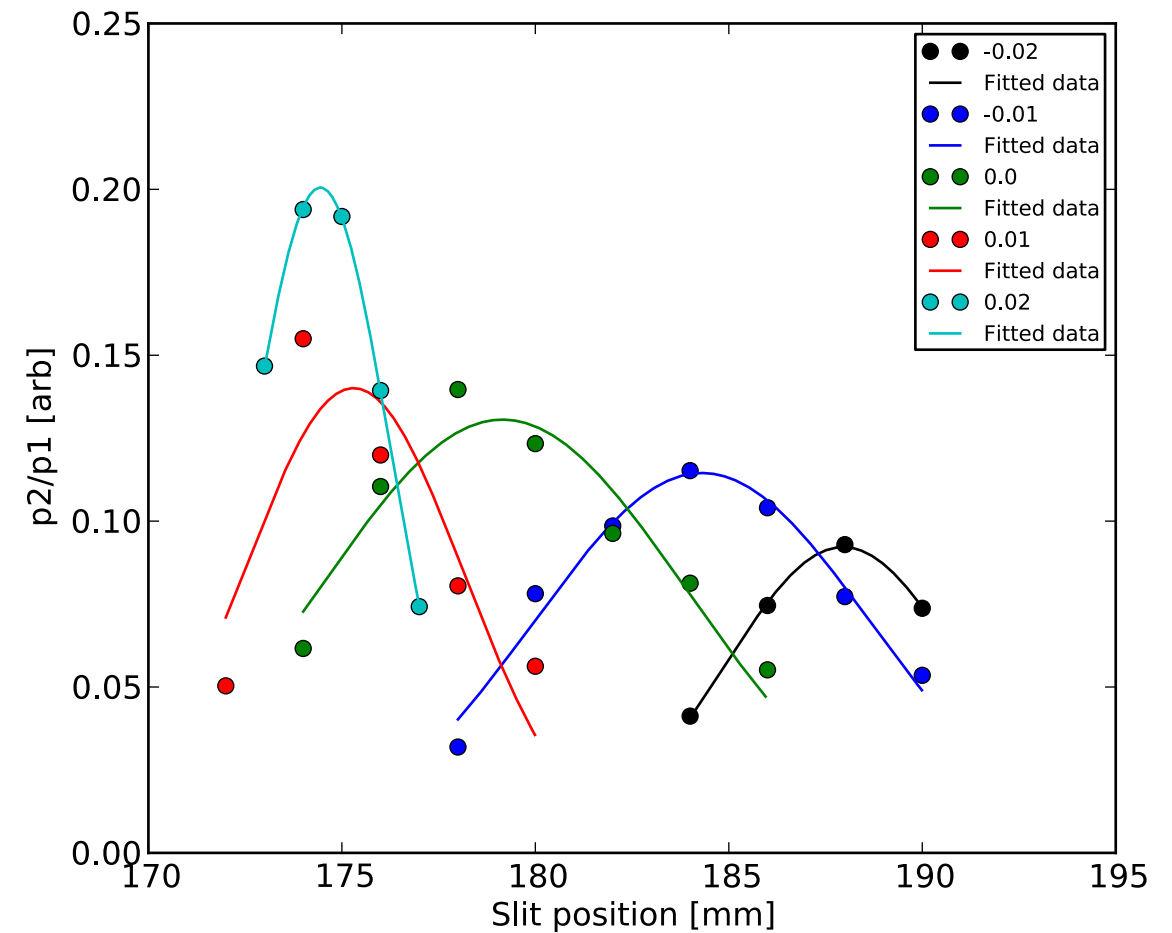


1. Setup transfer line with calculated magnet settings
2. Adjust BM2, Q6, BM3, Q7, Q8 by ratio (-2%, -1%, 0%, +1%, +2%)
  - Move slit after Q8 and record bunch monitor signals on M1 & M2 for each slit position
  - 'Peak ratio' =  $P2(\text{H- peak})/P1$

# Experimental data

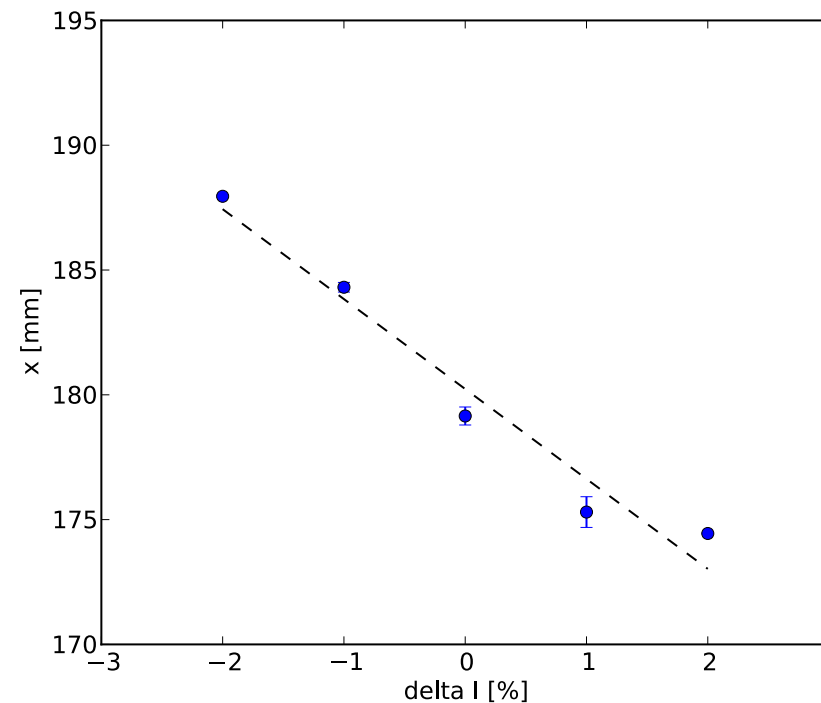
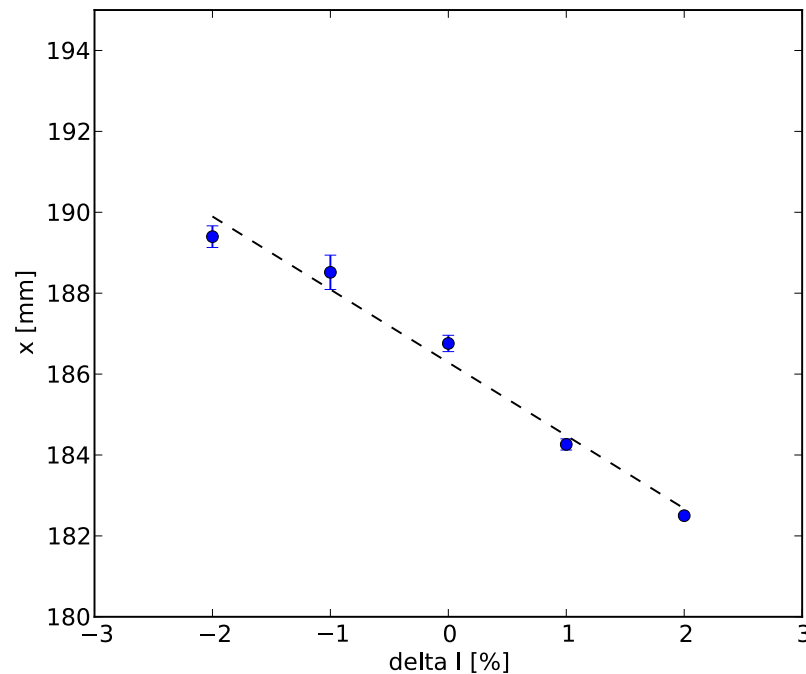


Setup 1  
(usual)



Setup 2  
30/06/14  
nb. lower transmission.

# Dispersion results



Setup 1

$dl \sim dB \sim -1.0 * dp$

Setup 2

$$D = dx/(dp/p) = -0.18m$$

cf. From inj. line model

$$D(sI) = -0.43I$$

$$D = dx/(dp/p) = -0.36m$$

cf. From inj. line model

$$D(sI) = -0.98I$$

We found that the measured dispersion is not that predicted by the model - by more than a factor of two.

# Why is the dispersion not as predicted?

- KURRI team have now re-measured this using real momentum change (adjusting the linac) & profile monitor and the result is consistent.
- In high D' region, D can easily vary with small error in magnet field setting.

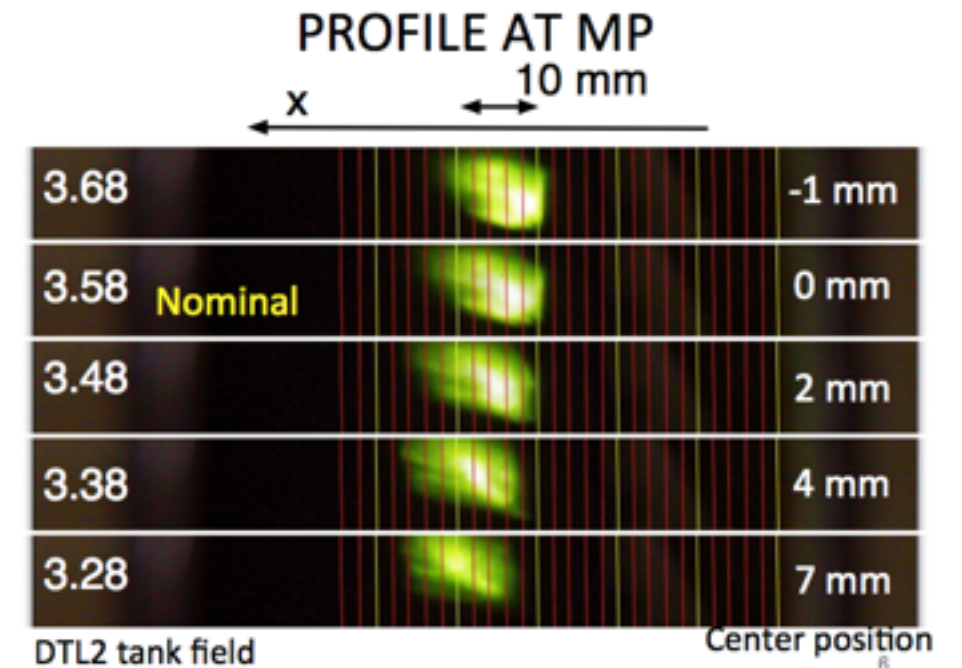
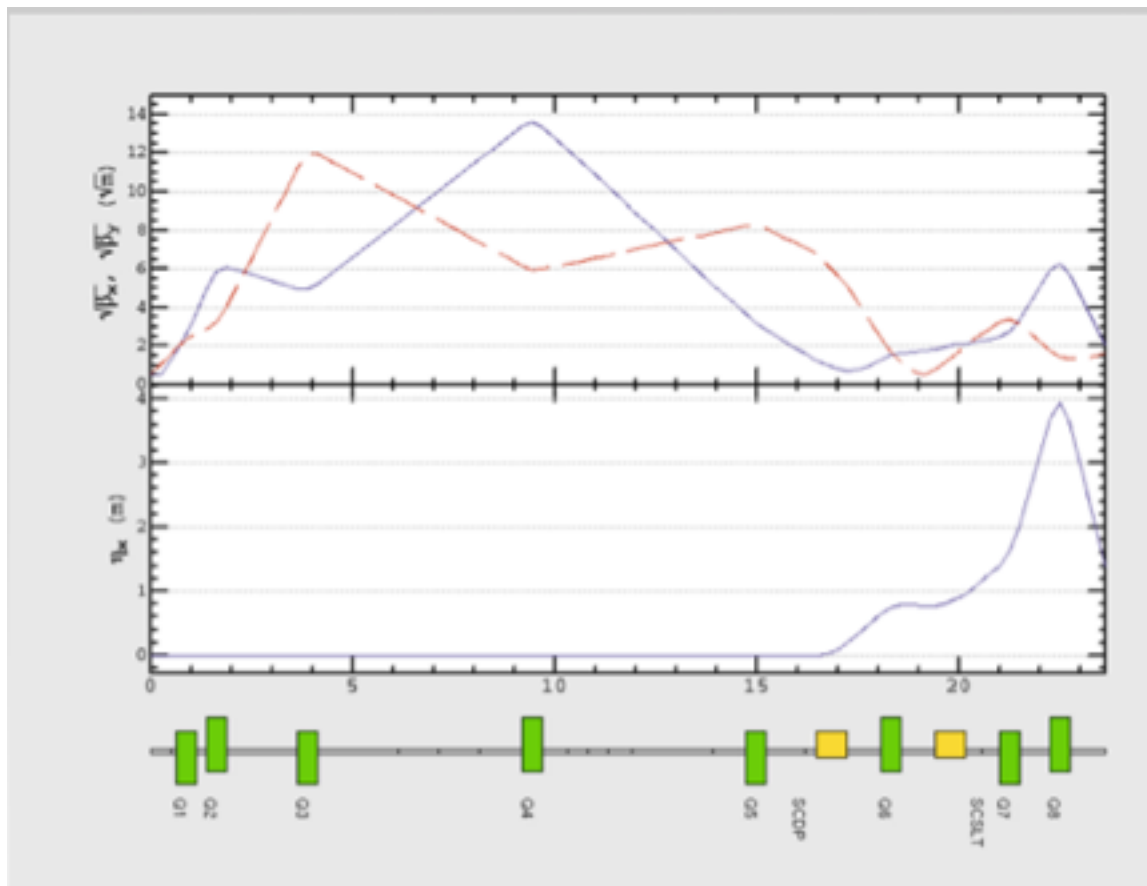


Image: T. Uesugi

It is very important to understand the real field of injection line magnets!



From Y. Ishi



# Dispersion and COD calculation

D. Kelliher

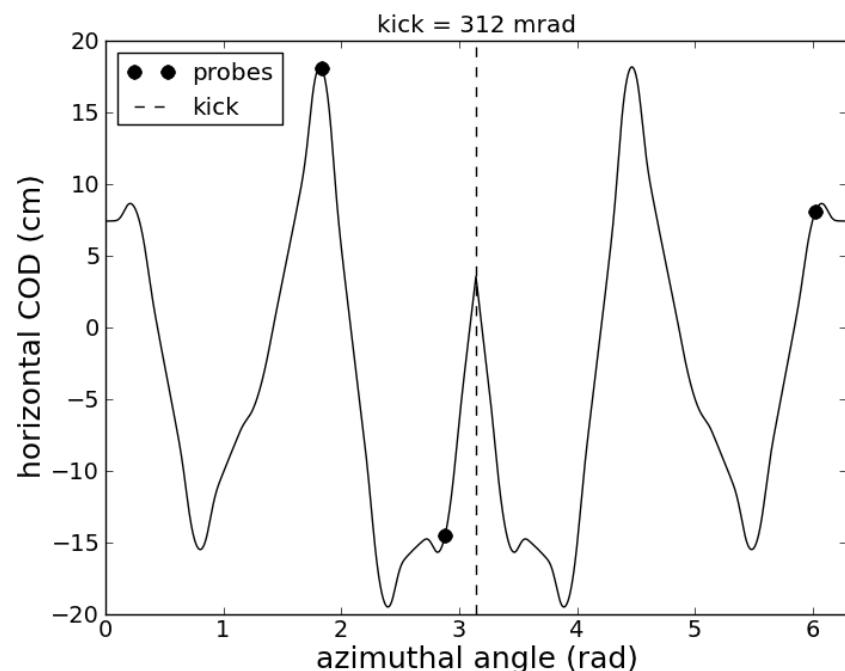
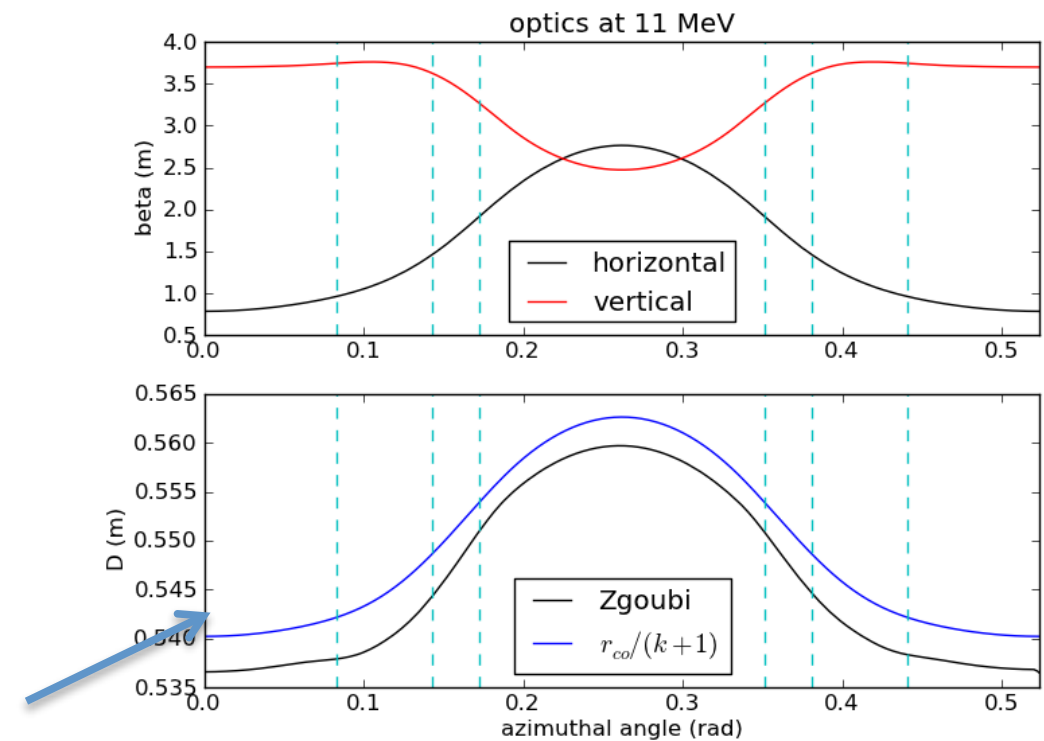
- Starting with field in a scaling FFAG

$$B_z = B_{z0} \left( \frac{r}{r_0} \right)^k$$

- Can show dispersion D is given by

$$D = \frac{r}{k+1} = \frac{r_0}{k+1} \left( \frac{p}{p_0} \right)^{\frac{1}{k+1}}$$

- Calculate off-momentum closed orbit in Zgoubi, compare dispersion with prediction

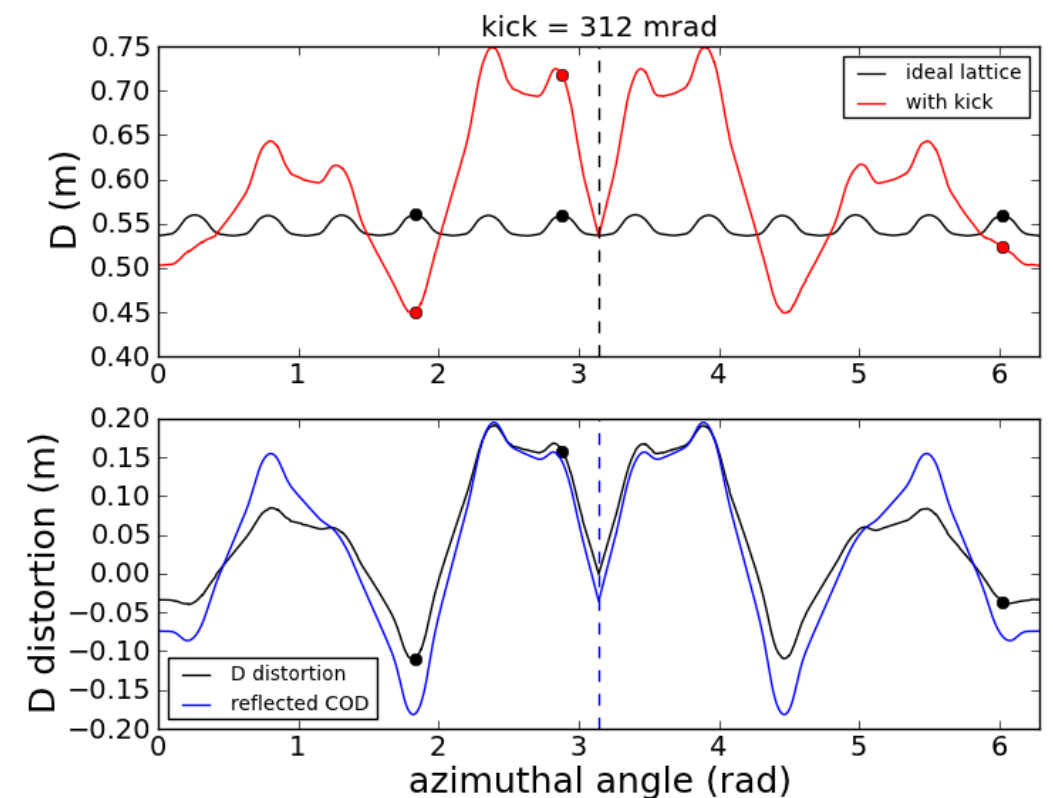


- A large (+/- 30 cm) COD is measured at the probes.
- We determined that the major source of COD is in the cavity region. Simulate in Zgoubi model by introducing kick in middle of single drift.

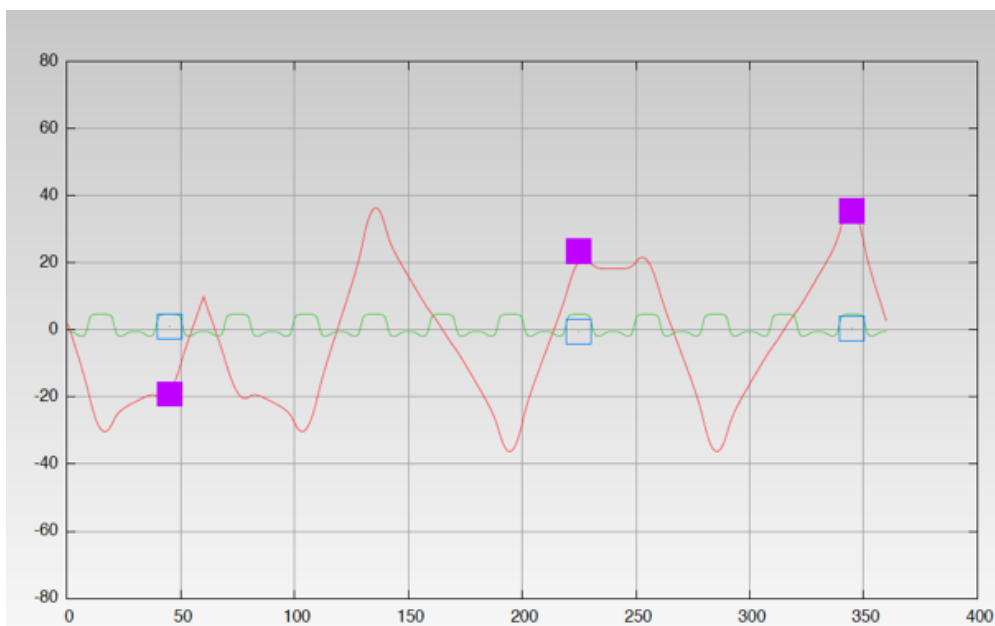
# Dispersion distortion

D. Kelliher

- What is effect of dipole kick on dispersion? Calculate the off-momentum COD in Zgoubi with the dipole kick and find  $D_{\text{kick}}$ .
- The dispersion distortion is defined as  $D_{\text{kick}} - D_{\text{ideal}}$ .
- The distortion in dispersion looks similar to the COD itself, though with the opposite sign.

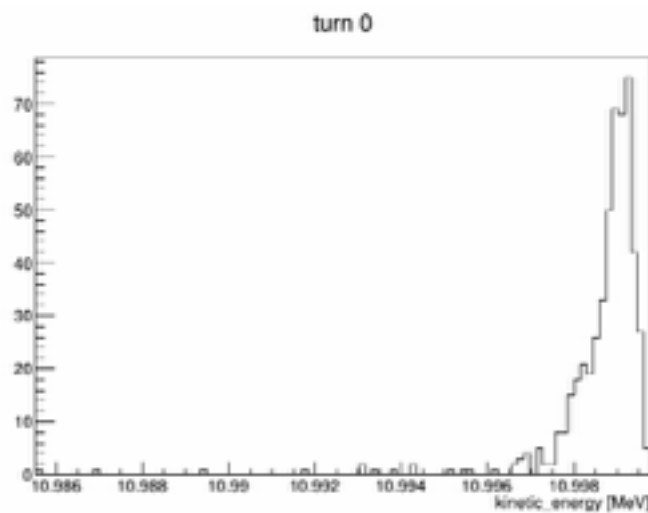


nb. COD measurement

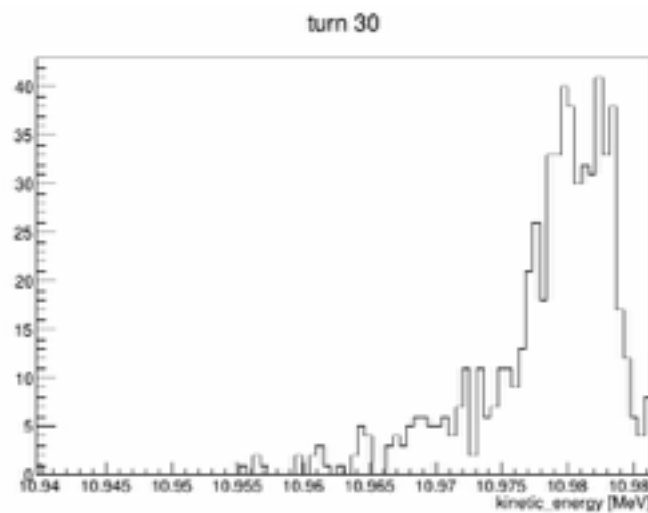


# Foil energy loss

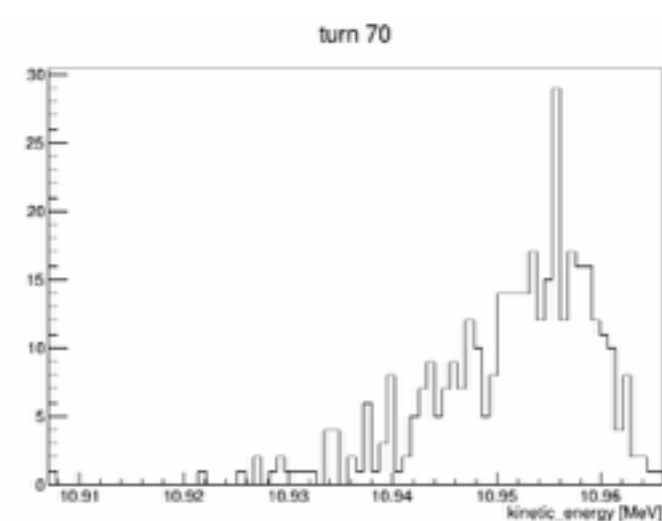
Simulation performed by C. Rogers in Geant 4 for varying target thicknesses to see energy loss and distribution



turn 0



turn 30



turn 70

20 ug/cm<sup>2</sup> foil

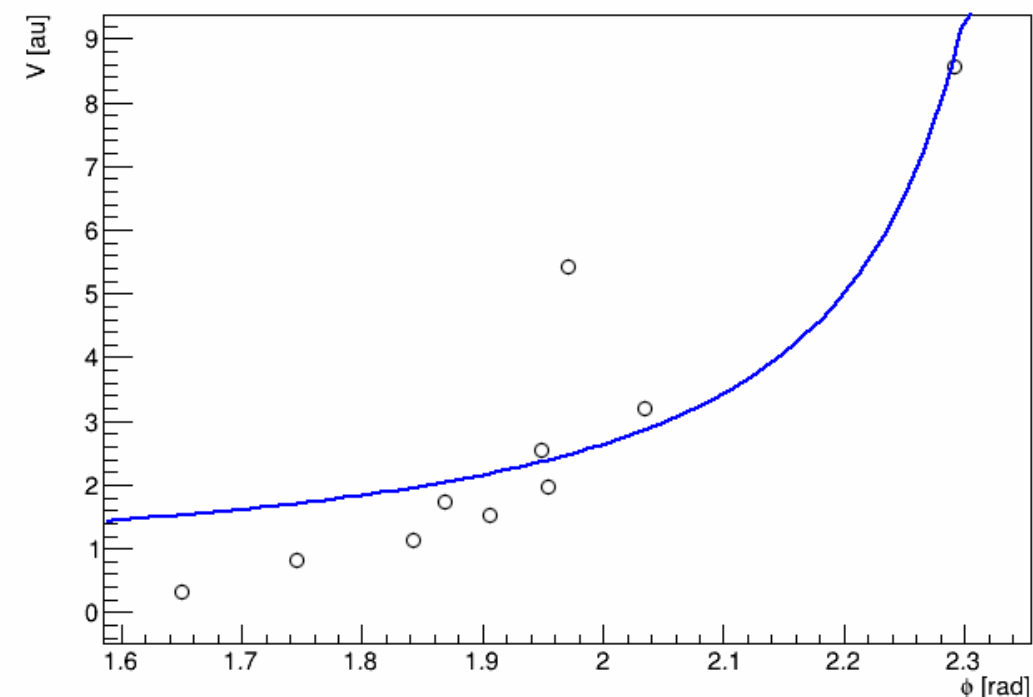
# Foil energy loss

Method: synchronous phase measurement as a function of RF voltage

1. check set RF frequency by circulating a bunch with RF off
2. set RF voltage & inject beam, find peaks in bunch monitor signal vs those in RF signal to determine phase offset
3. fit phase vs RF voltage to determine energy change per turn

$$dW = V_0 r_c \sin(\phi_s + \phi_c)$$

Preliminary data had some issues  
We have re-done the experiment  
Still analysing...

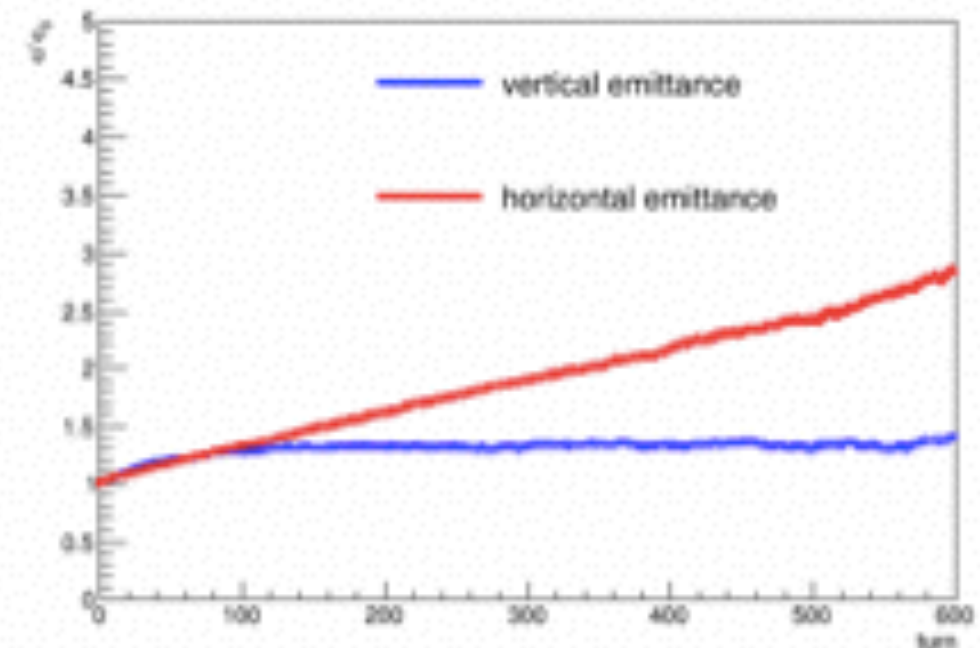




# Foil scattering

- Need to establish emittance growth from foil vs emittance growth from space charge

- Look at effect of foil on beam emittance
  - No RF
  - Inject 8 micron geometric emittance
  - Lose 50% of beam in first 200 turns
  - Injection cycle is  $\sim 160 - 1200$  turns



C. Rogers

Lower emittance growth for 10  $\mu\text{g}/\text{cm}^2$  foil

# Future work

- Understand injection line magnets to control dispersion
- Re-attempt dispersion matching (real  $p$  shift)
- Optics matching (in progress with new fluorescent monitor system)
- Full analysis of foil energy loss data
- Further simulation work including space charge
- Develop methods for emittance growth measurement

# Beam current/power

With linac & H<sup>-</sup> injection:

10nA average current ( $N=3.12 \text{ E}+9$  ppp)

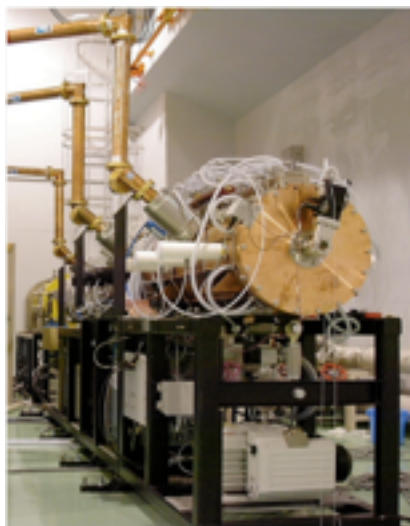
100 MeV, 20Hz rep rate

Bunch length < 100 us (injected), 0.1 us (extracted)

$$\text{Average beam power} = 10\text{E-}9 [\text{A}] * 100\text{E}+6 [\text{eV}] = 1 \text{ W}$$

$$\text{Duty cycle factor: } 0.1 \text{ us @ } 20\text{Hz} = 1/(0.1\text{E-}6 * 20) = 5\text{E}+5$$

$$\text{Instantaneous beam power} = 500 \text{ kW}$$



nb. Linac can in principle go up to 5mA & 100 Hz

This would give 5uA average current

$$\text{Average power} = 500 \text{ W}$$

$$\text{Instantaneous power (@100 Hz)} = 1\text{E}5 * 500\text{W} = 50 \text{ MW} !$$